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THE GLACIATED LANDSCAPE ACROSS THE FIRST WORLD WAR FRONT: QUANTITATIVE RECONSTRUCTIONS BASED ON DIGITIZED HISTORICAL IMAGES AND MODERN TECHNIQUES

Abstract: Carturan L., Bondesan A., Carton A., Cazorzi F., Cucchiaro S., De Marco J. & Piermattei L., *The glaciated landscape across the First World War front: quantitative reconstructions based on digitized historical images and modern techniques.* (IT ISSN 0391-9838, 2020).

The Italian/Austro-Hungarian front of the First World War (WWI) crossed several of the most glacierized groups in the Eastern Italian Alps. Photos taken by Austrian and Italian soldiers at that time document the state of various glaciers, in a period when measurements of length change were scarce or absent. Indeed, for many glaciers, the glaciological campaigns started or resumed only after the WWI, and this is the reason why the '1920' glacier expansion is not well documented in this geographic area. In this work, we propose a workflow aimed at the quantitative reconstruction of some Italian glaciers from WWI photos, by using the mono-photogrammetric method also known as *monoplotting*. The workflow can be applied to any digitized historical image of a glacier, even in the absence of information about the camera position and camera calibration parameters, provided that a digital elevation model (DEM) with metric or sub-metric resolution is available.

Key words: Glacier reconstructions, WWI front, Historical images, Monoplotting, Eastern Italian Alps, Military geosciences.

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Riassunto: Carturan L., Bondesan A., Carton A., Cazorzi F., Cucchiaro S., De Marco J. & Piermattei L., *Il paesaggio glacializzato lungo il fronte della Prima Guerra Mondiale: ricostruzioni quantitative basate su immagini storiche digitalizzate e tecnologie moderne.* (IT ISSN 0391-9838, 2020).

Durante il primo conflitto mondiale, il fronte tra Italia e Austria-Ungheria attraversava alcuni tra i più glacializzati gruppi montuosi delle Alpi Orientali Italiane. Le foto scattate dai soldati italiani e austriaci in quel periodo documentano lo stato di vari ghiacciai, in un periodo in cui le misurazioni frontali erano scarse o del tutto assenti. Infatti, per molti ghiacciai, le osservazioni sistematiche iniziarono o furono riprese solo dopo la fine del conflitto, e questa è la ragione per cui l'espansione del 1920 non è ben documentata in quest'area geografica. In questo lavoro si propone una procedura finalizzata alla ricostruzione quantitativa di alcuni ghiacciai italiani, a partire da foto scattate durante la prima guerra mondiale, utilizzando il metodo mono-fotogrammetrico altrimenti noto come *monoplotting.* La procedura può essere applicata a qualsiasi immagine digitale di un ghiacciaio, anche in assenza di informazioni riguardanti la posizione di scatto e i parametri di calibrazione della fotocamera, purché sia disponibile un modello digitale del terreno (DEM) con risoluzione metrica o sub-metrica.

Termini chiave: Ricostruzione glaciale, Fronte Prima Guerra Mondiale, Immagini storiche, Monoplotting, Alpi Orientali Italiane, Geoscienze militari.

INTRODUCTION

Glaciers are sensitive climatic indicators, important water sources, fascinating and appealing features of the alpine landscape. Furthermore, glaciers are considered morphogenetic factors relevant to geomorphological and hydrogeological risk management. The knowledge of their past fluctuations is the key for understanding their dynamics and their climate-related evolution (Wanner & *alii*, 2008). This knowledge enables climatic reconstructions in the past on a local and global scale (Mackintosh & *alii*, 2017), and to put the current glacier decline in a historical perspective (e.g., Zemp & *alii*, 2015).

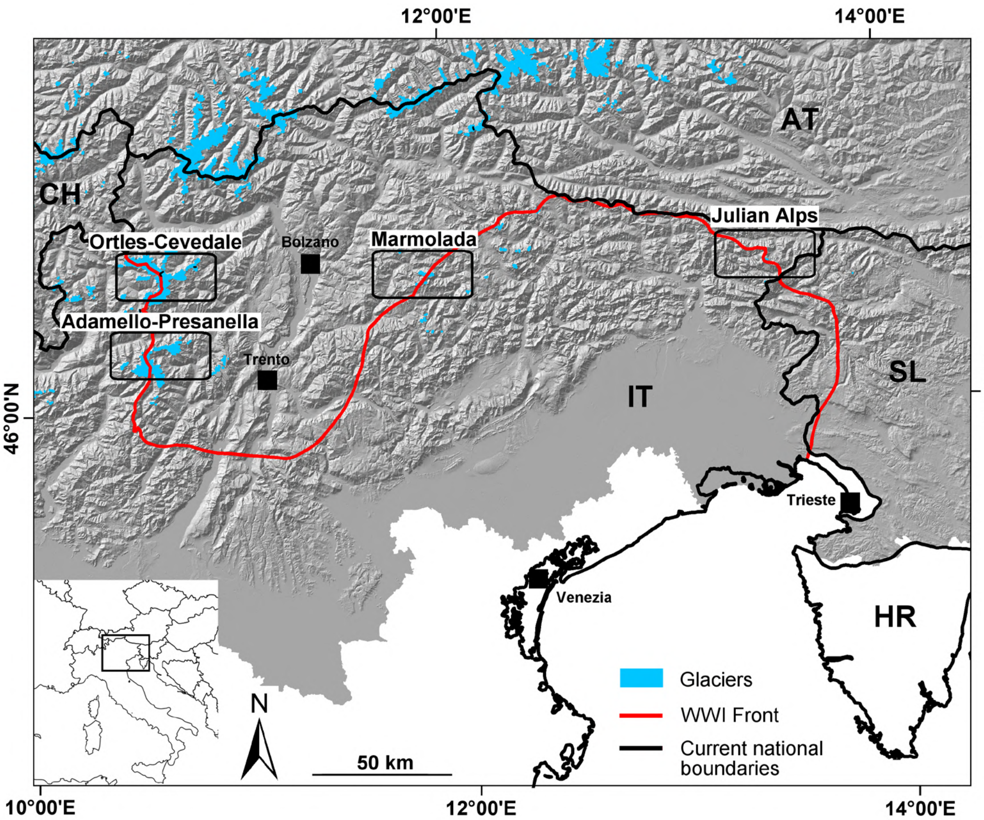

FIG. 1 - Location of the WWI front and of the mountain groups where the glaciers analysed in this work are located.

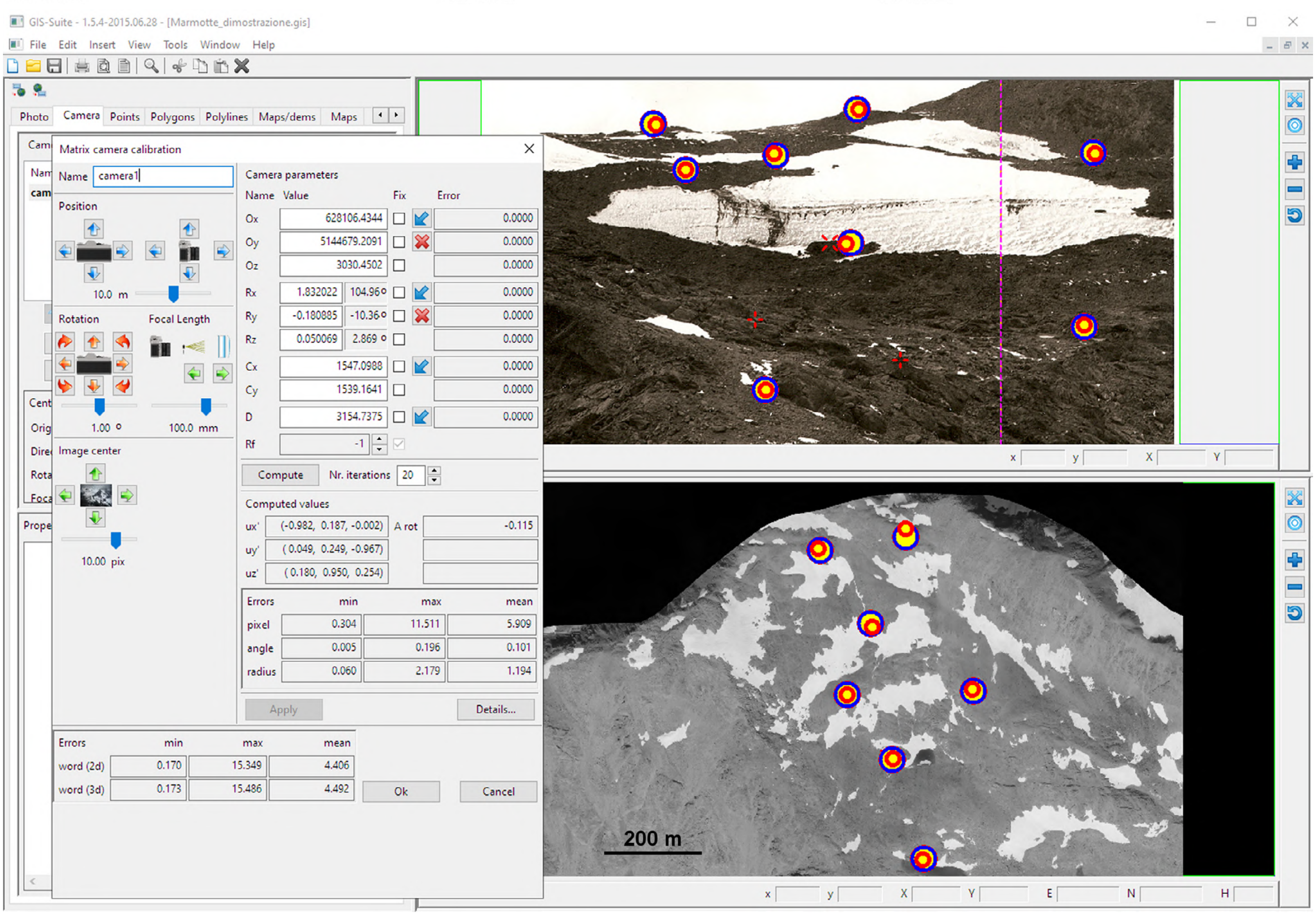

FIG. 2 - The graphical user interface of the WSL Monoplotting tool tested with a 1971 photo of the Marmotte Glacier in the Ortles-Cevedale (courtesy of Comitato Glaciologico Italiano).

Glacier mass balance and length changes are the two metrics normally used for reconstructing past fluctuations series of glaciers. However, length change measurements series are often discontinuous and require validation, and the mass balance measurements are available for few glaciers worldwide and only in recent decades (WGMS, 2015).

In the context of long, multi-secular glacier reconstructions, complementary sources of information such as historical-archival, glacio-archaeological and geomorphological data are of great importance because they provide spatial and temporal constraints that allow the completion and validation of direct measurement series, and their extension into the past (e.g., Nussbaumer & *alii*, 2007; Nussbaumer & Zumbühl, 2012). Old photos and maps, in particular, are useful for checking and integrating measurement series of glacier length change and for dating geomorphological evidences such as frontal and lateral moraines (Carturan & *alii*, 2014).

A unique source of unexploited historical information dating back to the First World War (WWI, 1915-1918) exists for several glaciers in the Eastern Italian Alps, in a period characterized by gaps in the measurement series. This information includes old topographic maps and photographs, which represent a good opportunity for glacier reconstructions. Unfortunately, such historical information is spread in a multitude of sources and often not yet digitized, and therefore it is hardly available to the scientific community or the society. The recent creation of digitized archives of maps (e.g., https://mapire.eu) and photos (e.g., www.bildarchivaustria.at, https://commons.wikimedia.org, https://www.oesta.gv.at/, http://www.europeana.eu) is a valuable effort to make some of this information available to a wider audience.

Among the photogrammetric tools recently developed, the mono-photogrammetric method, also known as *monoplotting*, seems promising for the analysis of the WWI glacier photos. This technique enables to obtain georeferenced cartographic and 3D data from single oblique photos, if a high-resolution digital elevation model (DEM) exists for the study area (Bozzini & *alii*, 2012). Although the first applications have proved effective (e.g., Steiner, 2011; Čekada & *alii*, 2014; Scapozza & *alii*, 2014; Hansche, 2017), the monoplotting has not been used extensively for glacier reconstructions so far.

In this paper, we propose a workflow for the analysis of photographs from the WWI, aimed at the reconstruction of glacier area, volume and snow line at that time by combining modern techniques of digital image processing and paleo-glacier reconstruction. This workflow is applied to several case studies in the Adamello - Presanella Group, the Ortles - Cevedale Group, the Dolomites, and the Julian Alps.

STUDY AREA AND METHODS

Case studies

The glaciers analysed in this study are located in massifs crossed by the Italian/Austro-Hungarian front during the WWI. Figure 1 depicts the four study areas and the WWI front just before the battle of Caporetto (24 October 1917).

The case studies were chosen according to i) the availability of high-quality photos suitable for analyses, and ii) the opportunity of exploring heterogeneous ice bodies. Point ii) was obtained including ice bodies ranging from glacierets smaller than 0.01 km^2 to mountain and valley glaciers that are among the largest in the Italian Alps, and with different source of nourishment (i.e., snow and drift snow or avalanche snow, table 1). In addition, we included glaciers from areas that are significantly different from a climatic point of view, especially in terms of precipitation, whose annual sums at the valley floor range between 900 mm in the Ortles - Cevedale and 2000-2500 mm in the Julian Alps. We have included glacierets that no longer exist to test the applicability of the method for the reconstruction of smaller ice bodies in areas of marginal glaciation during the Little Ice Age (LIA), or intermittent glaciation in the period afterwards. These small ice bodies are interesting because they were likely widespread, but hardly recognized and/or mapped due to the absence of geomorphological evidence or other sources of information. Their exclusion leads to an underestimation of the glaciated area in the past centuries, which deserves a quantification.

Application of the WSL Monoplotting tool for glacier reconstructions

The WSL Monoplotting tool was developed by researchers of the Swiss Federal Research Institute WSL, Insubric Ecosystem Research Group (Bozzini & *alii*, 2012; Conedera & *alii*, 2013). They developed an easily accessible, non-subject-specific (i.e., flexible and widely applicable), and user-friendly tool for georeferencing oblique photographs, which can be used by a broad number of non-expert potential users. These features led us to select the WSL Monoplotting tool among others (e.g., Corripio, 2004; Mitishita & *alii*, 2004; Fluehler & *alii*, 2005). The setup file and the user guide of the WSL Monoplotting tool can be accessed at the URL: https://www.wsl.ch/en/services-and-products/software-websites-and-apps/monoplotting-tool.html.

The tool connects a single digital oblique or aerial photo to a DEM, so that a line or a polygon drawn directly on the photo (for example the front or the perimeter of a glacier) is automatically converted into a vector polyline or polygon, whose vertices have object coordinates in the same coordinate system of the used DEM. Therefore, this vector data is already georeferenced and can be exported for being analysed using other software.

The tool accepts photos from any type of camera and lens; knowledge of camera parameters (for example lens distortions parameters or orientation parameters) is not mandatory. In addition to the photo and the DEM, the tool requires at least four Control Points (CPs) as input. The CPs should be clearly and precisely identifiable on both the photo and the DEM. They are necessary for assigning global coordinates to specific points in the photos. The CPs are generally selected as distinct features like rock outcrops, boulders, clasts. Obviously, the position of these features must be unchanged between the date of the photo and of the DEM survey (i.e., stable areas). The orthophotos and hillshades of the DEM can be also loaded into the tool to

TABLE 1 - Characteristics of the glaciers analysed in this study.

Ice body	WGI code	Mountain group	Type*	2006 area (km²)**	Major source of nourishment*	Reconstructions			
						WWI area	WWI surface topography	WWI front position	WWI snow line and firn line
Laghi d'Albiolo	Not inventoried	Ortles - Cevedale	Glacierets	0.00	Avalanche snow	X			
Gran Zebrù	IT4L01137016	Ortles - Cevedale	Mountain glacier	0.79	Snow and drift snow				X
Forni	IT4L01137024	Ortles - Cevedale	Valley glacier	11.31	Snow and drift snow				X
Rosole	IT4L01137021	Ortles - Cevedale	Mountain glacier	0.60	Snow and drift snow				X
Saline	IT4L00102508	Ortles - Cevedale	Mountain glacier	0.28	Snow and drift snow				X
Orientale di Presena	IT4L00102417	Adamello - Presanella	Mountain glacier	0.47	Snow and drift snow			X	X
Occidentale di Presena	IT4L00102418	Adamello - Presanella	Mountain glacier	0.39	Snow and drift snow				X
Lobbia	IT4L01011012	Adamello - Presanella	Valley glacier	6.43	Snow and drift snow				X
Mandrone	IT4L01024006	Adamello - Presanella	Valley glacier	16.39	Snow and drift snow				X
Principale della Marmolada	IT4L00101101	Marmolada	Mountain glacier	1.55	Snow and drift snow			X	X
Occidentale del Montasio	IT4L00003005	Montasio	Mountain glacier	0.07	Avalanche snow	X	X	X	

* during the WWI; ** according to Salvatore & *alii* (2015).

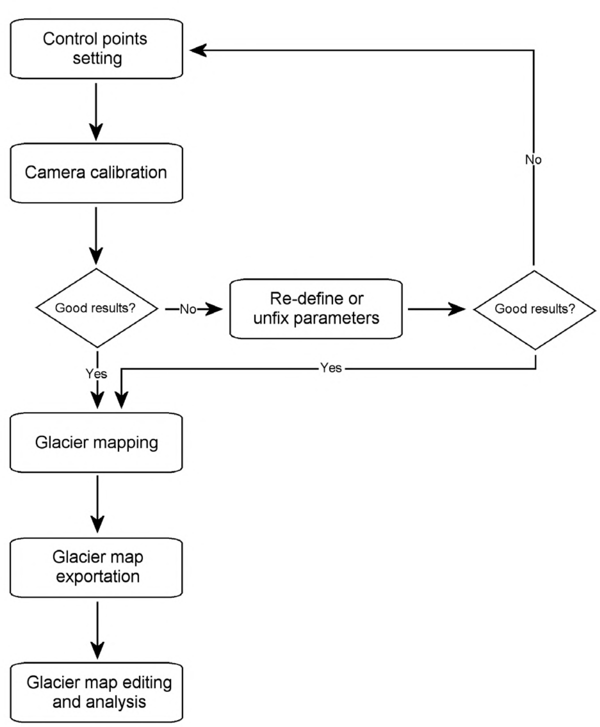

FIG. 3 - Schematic workflow for the application of the WLS Monoplotting tool for analyzing glacier changes using old photographs.

support the CPs selection. The DEM should be a regularly spaced grid, and should be of high-resolution (i.e., metric or sub-metric) to enhance the accuracy when assigning real-world coordinates to pixel coordinates.

The graphical user interface of WSL Monoplotting allows the simultaneous visualization of the oblique photo and of a raster (DEM, orthophoto, or hillshaded DEM), as shown in fig. 2, where the oblique photo is in the upper right corner, the raster is in the lower right corner, and the camera calibration window is on the left. The red circles are the CPs set by the user on both the photo and the raster, while the blue ones are the CPs projected after the camera calibration process. The red and blue circles should match and the residual errors (bottom left corner in fig. 2) should be as small as possible. The red crosses in the photo represent the set of CPs that are discarded (intentionally) during the camera calibration process.

In the first step of the workflow (fig. 3), we set as many CPs as possible in the oblique photos, trying to distribute them evenly. In the second step, we calibrated the camera. This step is iterative and involves a certain degree of subjectivity. In particular, different results in term of residual error can be obtained from different subsamples of CPs, and by fixing or unfixing specific parameters in the camera calibration window (fig. 2). We obtained the best results with camera parameters that are not fixed, and avoiding CPs positioned too close to the borders of the photo, where the lens distortion is highest. The goodness of the results was evaluated on the basis of residual 2D and 3D errors, which are calculated

FIG. 4 - Example of photos used for snow lines and firn lines determinations. The photo shows the Gran Zebrù Glacier (Ortles - Cevedale Group) in September 1917 (Bildarchivaustria.at).

by the software and displayed at the bottom left corner of the camera calibration window (fig. 2). Errors of about 10 m were considered acceptable for photos taken from a distance greater than one kilometer, whereas errors lower than 5 m were considered acceptable for closer distances.

The following steps consist of drawing the outline of the WWI glacier (front position or entire perimeter) in the georeferenced oblique photos, and exporting the line or polygon as a shapefile for further analyses in ArcGIS 10.3.1.

The oblique photos used in this work were downloaded from the digital archives available in the Web (www.bildarchivaustria.at, https://commons.wikimedia.org, https://www.oesta.gv.at/, http://www.europeana.eu). For the Montasio Occidentale Glacier we also used a photo taken from Desio (1923). The DEMs and orthophotos were retrieved from the National Geoportal of the Italian Ministry for Environment, Land and Sea Protection (http://wms.pcn.minambiente.it/ogc) and from the WebGIS services of the Friuli Venezia Giulia region and of the Provincia Autonoma di Trento.

Determination of snow lines and firn lines

Snow lines and firn lines were retrieved from late summer photos of several glaciers along the WWI front (table 1). Most of the photos were taken in mid-September 1917 (an example is shown in fig. 4) and were suitable for determining snow lines and firn lines due to the lack of recent snow, and the exposure of multi-year firn layers. The firn lines were detected at the margin of the lowest and oldest layer of firn visible in the photos.

The elevation of snow lines and firn lines was obtained from the DEM, using rock and debris areas outside the WWI glaciers that were at the same elevation. We estimated that the elevation error ranges between ±20 m. Finally, we compared the elevation of the retrieved firn lines with those observed from remote sensing imagery in late summer 2018. In this way, we calculated the variation between the 1910s and 2010s conditions.

RESULTS AND DISCUSSION

The Montasio Occidentale Glacier

The Montasio Occidentale Glacier is representative of small avalanche-fed glaciers, typical of the Dolomites and Julian Alps, with frontal moraines that are well preserved but lack a precise dating. For the reconstruction of the Montasio Occidentale Glacier we used two WWI photos (table 2, fig. 5)

The photo from the Jôf di Miezegnot shows the glacier frontal view and is suitable to map the glacier extent at that time, since the front is free from snow (fig. 5a). The residual error in georeferencing this photo is of 11.5 m, which is acceptable considering that it was taken from a distance of about 4 km. The glacier outline drawn from this photo is reliable in the middle and upper parts of the glacier, as it could be assessed from its intersection with the surrounding topography. However, the photo is not suitable to accurately reconstruct the lower part of the glacier because the glacier front is partially hidden by the frontal moraine (orange line in fig. 6a).

TABLE 2 - Number of Control Points used, distance between camera positions and ice bodies, and residual error estimates using WSL Monoplotting.

Ice body	No. CPs	Distance from camera position (km)	2D error (m)			3D error (m)		
			min	max	mean	min	max	mean
Laghi d'Albiolo (a)	6	0.5	0.170	1.637	0.737	0.258	1.756	0.848
Laghi d'Albiolo (b)	7	0.5	0.224	2.755	1.115	0.242	2.774	1.235
Orientale di Presena	7	1.5	1.958	5.820	2.851	2.120	7.646	3.571
Principale della Marmolada	7	3.5	4.739	19.140	9.363	6.143	19.529	10.904
Occidentale del Montasio (a-frontal view)	10	4.0	3.962	29.831	11.475	4.439	30.007	12.836
Occidentale del Montasio (b-lateral view)	4	0.1	0.018	5.566	2.324	0.068	5.628	2.354

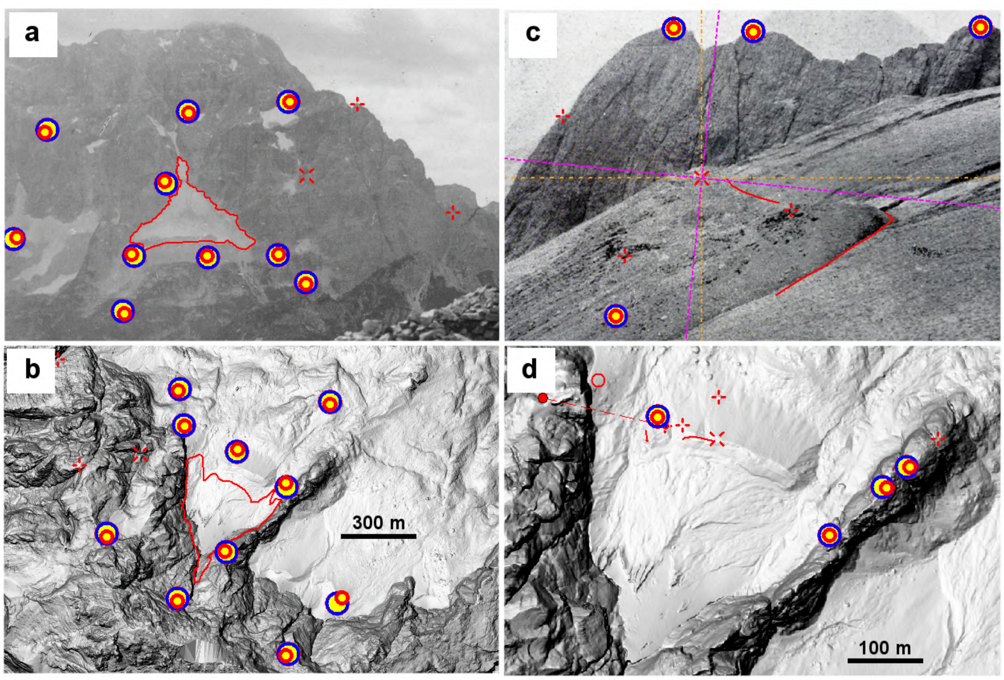

FIG. 5 - Frontal (a) and lateral (c) views of the Montasio Occidentale Glacier (Julian Alps, see fig. 1 for location) during the 1917-1920 period, and respective results (b, d) of the georeferencing in the WSL Monoplotting tool (hillshade of the 1 m 2008 DEM in the background, http://irdat.regione.fvg.it). Red lines are digitized glacier outlines or front positions.

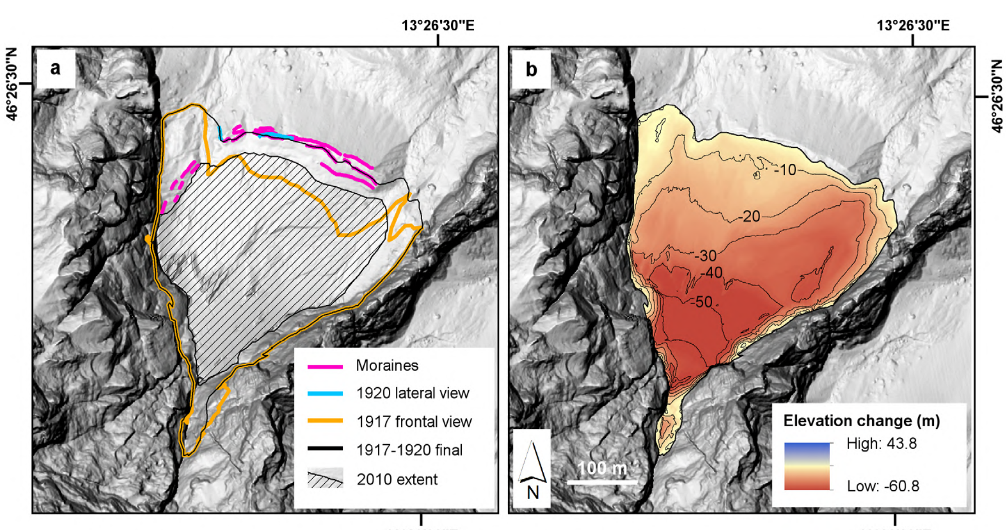

FIG. 6 - (a) The frontal, lateral, and combined outlines of the Montasio Occidentale Glacier in the period from 1917 and 1920, compared to the 2010 glacier extent (Carturan & *alii*, 2013). (b) Elevation changes reconstructed between the WWI period and 2010.

To overcome this issue, we georeferenced a second photo taken by Ardito Desio in the summer of 1920 (Desio, 1923) that shows the glacier from a lateral perspective (fig. 5c). This photo shows the left orographic side of the glacier front and is useful to map the front position immediately after the WWI. We were able to locate the front of the glacier with high accuracy, with a residual error of 2.3 m. This location is almost coincident with a moraine ridge in close proximity to the outermost late-Holocene moraine mapped for this glacier (Carturan & *alii*, 2013). Therefore, the lower limit of the glacier obtained from the frontal view was adjusted to correspond to the moraine left by the glacier between the 1910s and 1920s. We used a georeferenced map of the glacier, surveyed by Ardito Desio in 1920 using a topographic compass (Desio, 1923), to further constrain the lower limit of the glacier where the moraines have been eroded.

With the help of the same map, we reconstructed the surface topography of the glacier during the WWI. Starting from DEM elevations along the WWI limit, we designed contour lines at intervals of 10 m, parallel to those of the Desio's map, and then converted the polyline vertices into a topographic surface using the Spline tool of ArcGIS 10.3.1.

The comparison between the reconstructed geometry during (or shortly after) the WWI and the 2010 glacier geometry (area, surface topography and ice thickness reported in Carturan & *alii*, 2013) reveals a decrease of 34% in area and 73% in volume. Considering the proximity of the WWI front to the LIA maximum position, we can assume these variations as representative of the period between 1850 and 2010 (although slightly underestimated).

Compared to Alpine-wide estimates of 60% glacier area shrinking provided by Haeberli & *alii* (2019) for the same period, these results confirm, on a secular time scale, the lower climatic sensitivity of this glacier. This lower sensitivity depends on favourable topo-climatic conditions such as avalanche feeding, debris cover, and shadowing, as already highlighted in previous works (Carturan & *alii*, 2013 and references therein; De Marco & *alii*, 2020). This is further confirmed by the average geodetic mass balance between 1917 and 2010 (-0.29 m y^{-1} w.e.), which is 23% higher than the average value for the European Alps estimated by Zemp & *alii* (2015).

The Marmolada Glacier

The Marmolada Glacier is one of the most iconic glaciers along the Italian/Austro-Hungarian WWI front. At that time, it was much larger and thicker than now, and it is well known for the 'ice city', a web of tunnels – a total of 12 km, along with barracks, kitchens, sanatoriums, stores, and even a chapel – dug inside it by Austro-Hungarian soldiers (Handl L., 1916 and 1917; Bondesan & *alii*, 2015).

A photo taken in late summer of 1916, from a distance of about 3.5 km, offers a nice view of the glacier with the lower margin that was almost free from snow (fig. 7a). The residual error of the photo georeferencing using the WLS Monoplotting tool was of 9.4 m. The raw generated shapefile of the lower limit of the glacier required only minor adjustments due to local inconsistencies over small snowfields.

The moraine complex of the Marmolada Glacier is characterized by generally small and fragmented deposits, due to the steepness of the proglacial terrain and to the low amount of debris entrained by the glacier (Mattana, 1995). There are two main series of deposits, the uppermost and youngest of which is more discontinuous and only locally organized in well-visible ridges (fig. 8). These uppermost moraine ridges have not been dated so far.

The reconstructed 1916 lower limit of the glacier shows that, during the WWI, the fronts were only 40-50 m upstream of the uppermost moraine series. Observing the bulgy aspect of the fronts in 1916 and in other photos available for 1917, and the low elevation of the firn line in the 1910s (Section 3.5), we can assume that the glacier was advancing and that these moraines, not visible in the 1916 photo, were deposited shortly after the WWI. Our reconstruction shows that during the WWI the main (central) tongue was about 350 m upstream of the maximum position reached during the late Holocene, and that the total cumulated retreat in 2015 was of 1300 m (i.e., 62% of the initial glacier length).

The Presena Orientale Glacier

Several nice photos of this glacier are available for the second half of the 1910s, because it is located near the Presena Occidentale Glacier, the first battlefield in history on a glacier. These photos depict the glacier with advancing fronts and enable recognizing snow lines and firn lines on both glaciers. The late summer photo from 1917 shown in fig. 9a was used for reconstructing the lower margin of the glacier. Thanks to the high quality of the photo (low distortion and high resolution) and to the relatively low distance of the photographer from the glacier (about 1.5 km), the georeferencing was accurate, with a residual error of only 5.8 m.

The moraine complex of the Presena Orientale Glacier is well defined and preserved. Three series of moraines close to the lower limit of the moraine complex, only 50 m apart from each other, indicate three different advance (or steady-state) phases in very similar positions during the Late Holocene. Between the current front of the glacier and these lowest moraines, there is another moraine series, which indicates a later advance of the glacier (fig. 10). It is possible to hypothesize that these younger moraines belong to the expansion of Alpine glaciers during the late 1910s and the beginning of the 1920s (Zemp & *alii*, 2007). However, in the absence of other evidence, it is not possible to confirm the period of formation of these moraines.

The reconstructed lower margin of the glacier during the WWI period is almost coincident with these younger moraines. On the outer sides of the fronts, the advance was almost complete, whereas their inner side had yet to reach its maximum position. It is possible that the rock outcrop between the two tongues of the glacier locally decelerated the ice flux, delaying the achievement of the most advanced position. A possible alternative explanation is that the inner side of fronts had already begun to retreat in 1917. On the basis of these results we can date the youngest moraines of the Presena Orientale Glacier to the late 1910s or early 1920s. The glacier is now strongly reduced in area and volume, compared to the WWI period. The cumulated retreat from the Late Holocene maximum was 550 m during the WWI, and 1150 m in 2015 (-70% of the initial length).

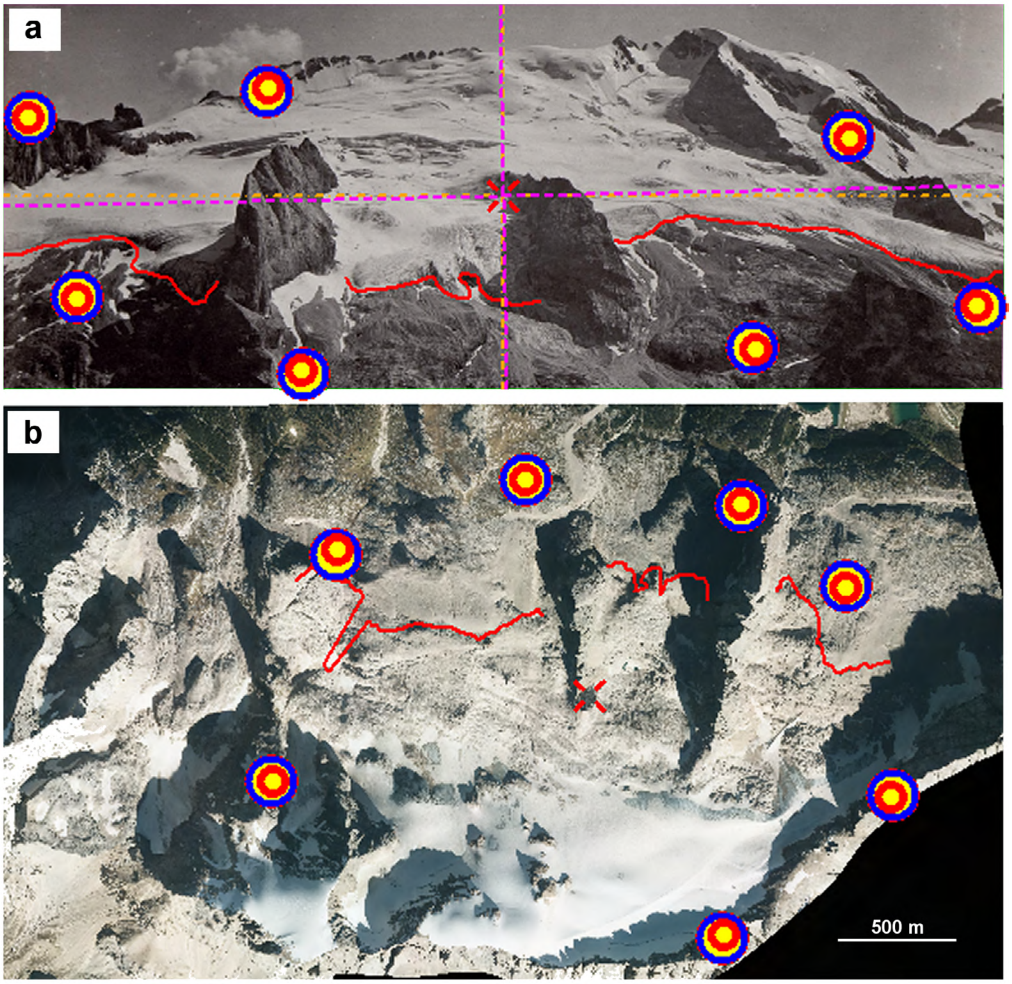

FIG. 7 - Frontal view (a) of the Marmolada Glacier (see fig. 1 for location) in 1916, and results (b) of the georeferencing in the WSL Monoplotting tool (Ortofoto Digitale 2015 - PAT Ufficio Sistemi Informativi - Servizio Geologico (Provincia Autonoma di Trento) - patn.maps.arcgis.com). Red lines are digitized glacier outlines or front positions.

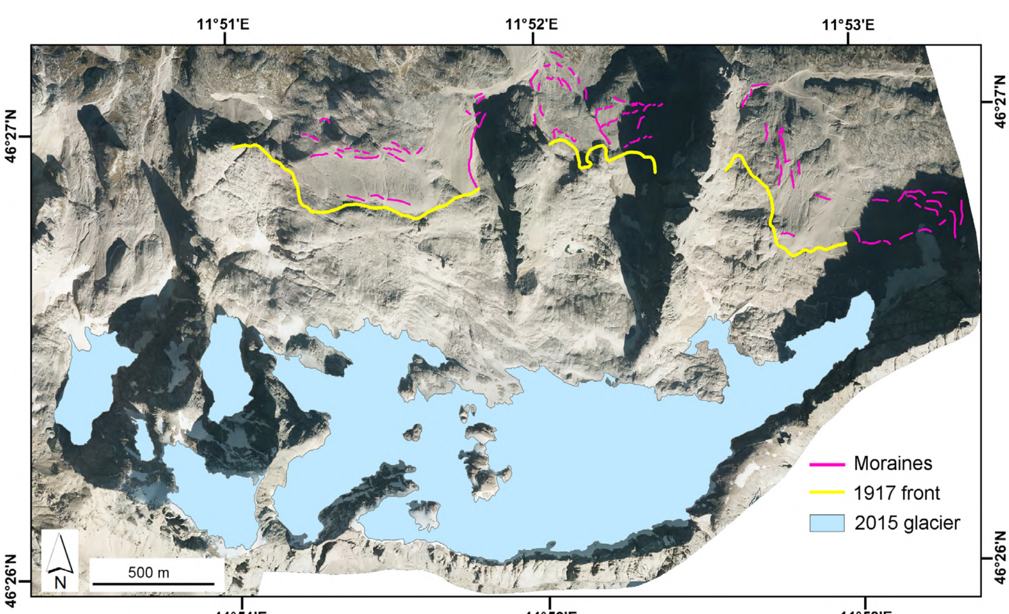

FIG. 8 - The reconstructed front position of the Marmolada Glacier in 1916, its moraine complex and the 2015 glacier extent (Salvatore & *alii*, 2015; Nextdataproject.it).

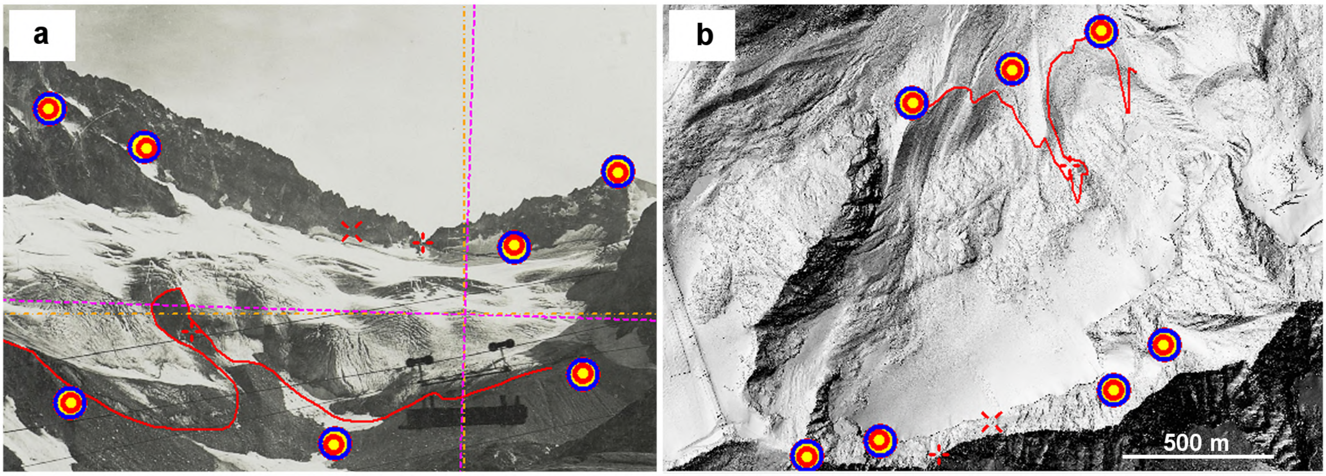

FIG. 9 - Frontal view (a) of the Presena Orientale Glacier (Adamello Presanella Group, see fig. 1 for location) in 1917, and results (b) of the georeferencing in the WSL Monoplotting tool (hillshade of the 2 m 2007 DEM in the background, siat.provincia.tn.it/stem/). Red lines are digitized glacier outlines or front positions.

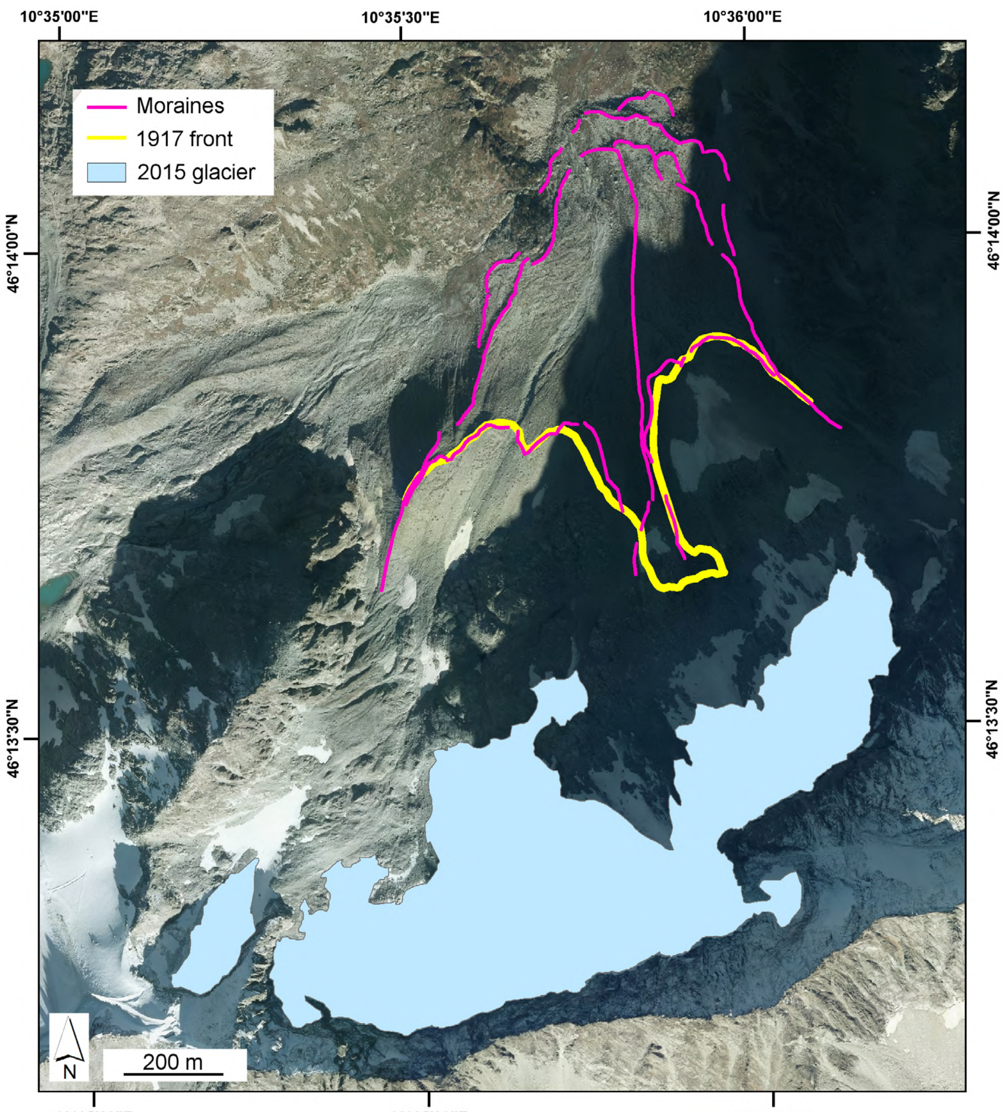

FIG. 10 - The reconstructed front position of the Presena Orientale Glacier in 1917, its moraine complex and the 2015 glacier extent (Salvatore & *alii*, 2015; nextdataproject.it). The background is the Ortofoto Digitale 2015 - PAT Ufficio Sistemi Informativi - Servizio Geologico (Provincia Autonoma di Trento) - patn.maps.arcgis.com.

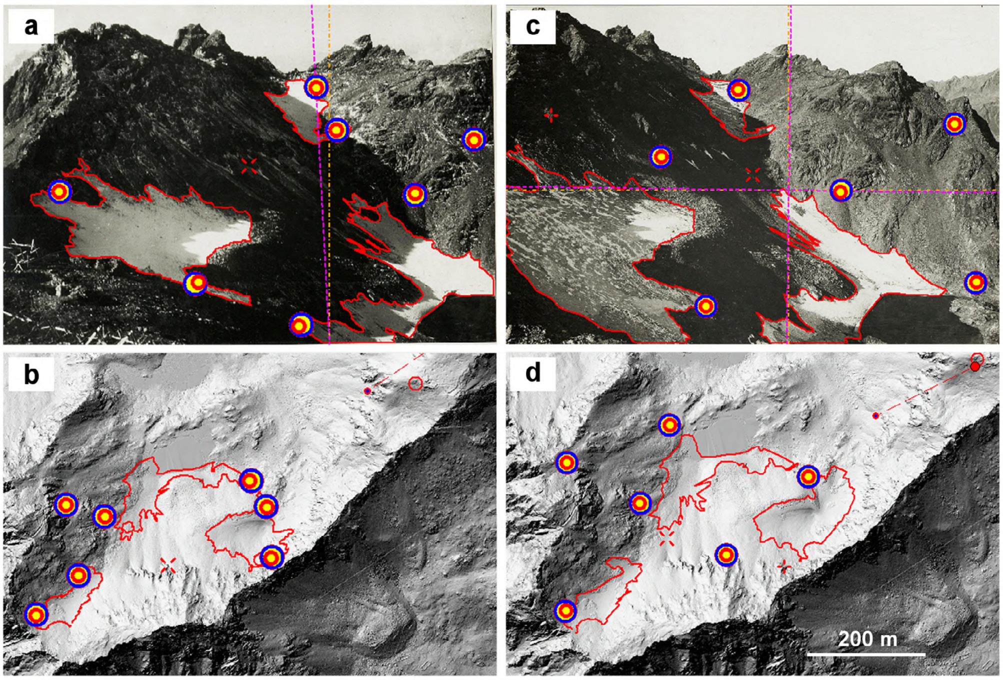

FIG. 11 - Lateral views (a, c) of the Laghetti d'Albiolo glacierets (Ortles - Cevedale Group, see fig. 1 for location) in September 1917 from two slightly different positions, and respective results (b, d) of the georeferencing in the WSL Monoplotting tool (hillshade of the 2 m 2007 DEM in the background, siat.provincia.tn.it/stem/). Red lines are digitized glacier outlines or front positions.

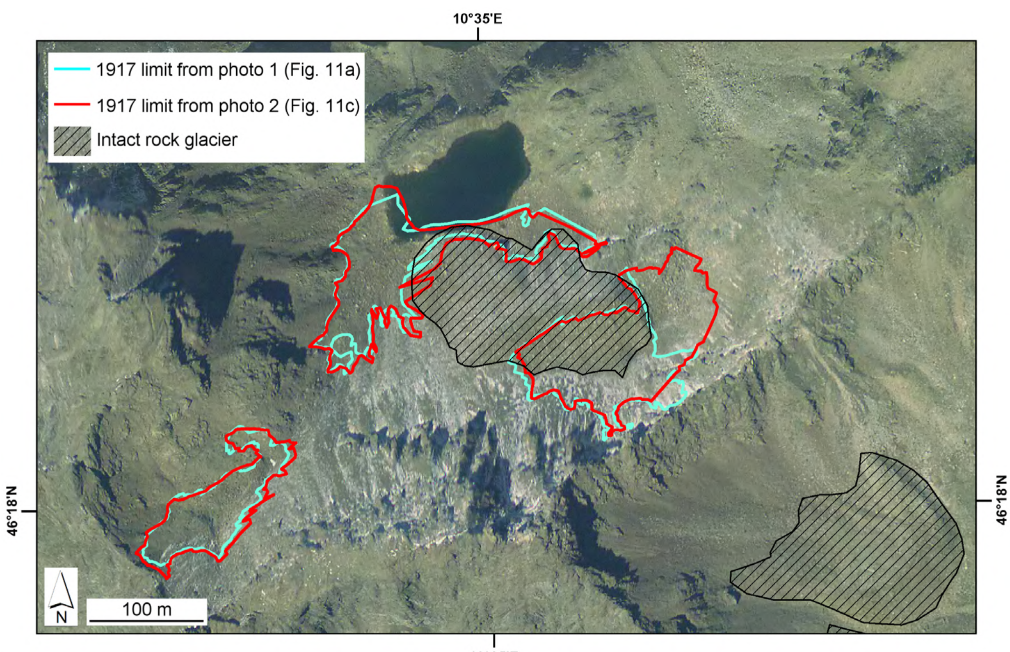

FIG. 12 - Unedited outlines of the Laghetti d'Albiolo glacierets obtained from the two photos shown in fig. 11. The background is the 2006 digital orthophoto available through the Web Map Service (WMS, http://wms.pcn.minambiente.it/ogc?map=/ms_ogc/WMS_v1.3/raster/ortofoto_colore_06.map).

The Laghi d'Albiolo glacierets

Talus slopes and moraines that are almost free of vegetation characterize the cirque on the northern side of the Torrione d'Albiolo (2969 m a.s.l., in the Ortles - Cevedale Group). A rock glacier develops on the outer side of a small moraine, and its front reaches the Lago Superiore d'Albiolo (2745 m a.s.l.). According to the regional rock glacier inventory (Seppi & *alii*, 2012), this rock glacier is intact (*sensu* Haeberli, 1985), and its morphology and surface characteristics suggest that it is likely active. Other small periglacial landforms, mainly gelifluction/solifluction lobes, are observable in this area.

The elevation of the site, between 2759 and 2900 m a.s.l., its northern exposure, and the high snow accumulation due to avalanches, suggest that glacierets or even a small glacier might have existed in this cirque during the LIA, or in favourable periods during the 20th Century. The current persistence of snow fields until mid-summer and the documented existence of small ice bodies in areas with similar characteristics of the Ortles-Cevedale Group (Desio, 1967) support this hypothesis. However, it is difficult to prove this only with geomorphological observations, since the existing deposits are mostly sparse and deformed by periglacial processes. Moreover, they are not dated.

During the WWI, the Torrione d'Albiolo was a strategic point of the Italian/Austro-Hungarian front, repeatedly attacked by the Italian army. One of these actions was successful (21 August 1915), but the Austrian soldiers regained it shortly after (23 September 1915) and kept the position until the end of the war (4 November 1918).

Among the available photos taken by the Austrian soldiers, two photos from an unnamed peak, located 500 m NE of the cirque, clearly show the presence of three glacierets in this cirque in September 1917. We name them 'glacierets' because there are three different layers of residual snow and firn visible (foreground of fig. 11c), which indicate the persistence of these ice bodies for at least three consecutive years. On the other hand, we can exclude that they were small glaciers because of the irregular shape, the absence of a distinct (upper) accumulation area and a (lower) ablation area, and the absence of features indicating movement (e.g., crevasses).

We decided to map these glacierets using both photos, in order to test the replicability of results obtained from the workflow implemented in this work. The georeferencing was quite accurate in both cases with a residual error of 1.6 m and 2.8 m. However, a complete outline of the glacierets was obtained only from the photo with the most favourable point of view (fig. 11c).

The two raw outlines drawn in Monoplotting and imported in ArcGIS are shown in fig. 12, without adjustments. As can be seen, there are small areas with zigzags, which correspond to partial visual obstructions at the margin of glacierets. The most problematic area is near to the front of the rock glacier, which partially masks the margin of a glacieret. The maximum discrepancy of limits in areas without obstructions is of 4-5 m, in line with the aforementioned residual errors. The difference in areal extent varies between 891 m^2 (13%) for the western glacieret and 1899 m^2 (15%) for the central glacieret. Considering only the outlines that are not occluded by the local topography, we can quantify the total area of the three ice bodies in 3.5 ha.

On the basis of these results, we can conclude that this site, and similar sites in the Ortles - Cevedale Group, likely hosted small ice bodies (glacierets or small glaciers) not only in the LIA but also during favourable periods afterwards. In this specific area, glacierets reconstructed in the WWI combined with geomorphological evidence, debris weathering, vegetation cover and snow cover patterns during mid- and late-summer (retrieved for recent years from satellite imagery), lead us to hypothesize that at the LIA maximum this area was occupied by 1-2 glacierets or small glaciers, with a total area of about 8-10 ha.

Snow lines and firn lines

In the analysed photos, the snow and firn lines were in close vicinity and, in some cases, coincided (table 3). In one case, (Marmolada in September 1917), the firn line was buried under residual snow. In the Ortles - Cevedale Group, there were up to three distinct layers of firn below the snow line of September 1917, whereas in other cases only one or two layers of firn were visible. In the Forni and Gran Zebrù glaciers, the uppermost firn layer was just a little darker than the residual snow of 1917, and for this reason it can be attributed to 1916. The lower layers of firn are significantly darker and probably more than one year older than 1916 (fig. 4). The 1915 photo of the Marmolada Glacier shows a snow line that was above the firn line, with conditions that were similar to 1917 on the Ortles - Cevedale Group. This suggests that the 1915 mass balance could have been lower than in previous years and, assuming similar regional conditions, the darkest firn layers visible in the Forni and Gran Zebrù glaciers should be attributed to 1913, 1914 or even older years.

TABLE 3 - Snow and firn lines retrieved from WWI photos on several glaciers along the WWI Italian-Austrian front, compared to current firn lines obtained from satellite imagery.

Mountain Group	Glacier	Date of the photo	WWI Snow line (m)	WWI Firn line (m) [AAR]	2018 Firn line (m)	Firn line variation (m)
Ortles - Cevedale	Gran Zebrù	(Sept.? 1917)	2970	2950 [0.80]		
Ortles - Cevedale	Forni	22/10/1917	2970	2950 [0.70]		
Ortles - Cevedale	Rosole	(Sept.? 1917)	3000	3000 [0.75]		
Ortles - Cevedale	Saline	Sept. 1917	3000	2900 [0.70]		
Ortles - Cevedale mean*				2950 [0.74]	3300	+350
Adamello - Presanella	Presena W	11/09/1917	2700	2700 [0.90]		
Adamello - Presanella	Presena E	13/09/1917	2600	2600 [0.75]		
Adamello - Presanella	Lobbia	13/09/1917	2800	2800 [0.85]		
Adamello - Presanella	Mandrone	13/09/1917	2850	2850 [0.85]		
Adamello - Presanella mean*				2783 [0.87]	3250	+467
Marmolada	Marmolada	(Sept.?) 1915	2710	2700 [0.80]		
Marmolada	Marmolada	24/09/1917	2650	buried		
Marmolada mean*				2700 [0.80]	3050	+350

* considering glaciers where the snow and firn limits are not lowered by avalanches.

These observations provide direct evidence that the 1910s have been favourable for the analysed glaciers. Since the firn lines are indicative of the long-term Equilibrium Line Altitude (ELA) (Kargel & *alii*, 2014), we can state that in the 1910s the ELA was rather low, and consequently the accumulation area ratios (AAR) were higher than normally required for zero-budget conditions (table 3). This is in agreement with the shape of most glacier fronts visible in the WWI photos, which indicates an expansion of glaciers at that time. In addition, low ELAs and high AARs, combined with the front positions visible in the WWI photos, provide solid evidence that most of the moraines found on these glaciers' forefields, between those of the Late-Holocene maximum and those of the 1980s, were deposited in the late 1910s or early 1920s.

Long-term reconstructed ELAs were comparable or even lower that the zero-budget ELA calculated from the LIA glacier geometries in these mountain groups. For example, Baroni & *alii*, (2017) calculated a LIA ELA of 3025-3050 m a.s.l. for the Careser and La Mare glaciers in the Ortles-Cevedale Group. Pelfini (1994) calculated a mean LIA ELA of 2960 m for the Gran Zebrù, Rosole and Forni glaciers, compared to our mean firn line of 2966 m for the same glaciers. Baroni and Carton (1990) calculated a LIA ELA of 2855 m for the Lobbia Glacier, which is higher than the firn line at 2800 m observed in the WWI photos.

These results highlight high variability of glacier ELAs in the past, which cannot be fully reconstructed from multi-temporal comparisons of glacier geometries alone. Indeed, glacier geometry variations are affected by glacier-specific response times, and are typically delayed and filtered response to sustained changes in ELA over the medium to long term, thus hiding its inter-annual variability. WWI photos provide rare documentation of high inter-decadal and inter-annual ELA variability in the past, which is relevant because for the vast majority of glaciers this information is only accessible from systematic glacier mass balance observations, limited to recent decades.

A quantification of ELA variations based on current and past glacier geometries is generally obtained comparing zero-budget ELAs (e.g., Porter, 1975). However, existing glaciers are far from equilibrium with the current climatic conditions, and therefore their zero-budget ELA is much lower than the actual ELA, observed e.g. from satellite imagery. In table 3 we compare the WWI firn lines with the 2018 firn lines, retrieved from the European Space Agency (ESA) Sentinel-2 images in late summer. The Mandrone Glacier clearly exemplifies the discrepancy between the large variation of the ELA obtained from firn lines (about 400 m) and the much smaller variation of the zero-budget ELA (100-150 m). The latest is not only influenced by the long response time of the glacier but it is also affected by the sustained lowering of its surface (disequilibrium response).

CONCLUSIONS

In this work, we have successfully tested the mono-photogrammetric (or monoplotting) method, applying the WSL Monoplotting tool for reconstructing the geometry of several ice bodies along the Italian-Austrian front during the WWI. The results are satisfactory in terms of planimetric accuracy and repeatability, with residual errors of a few metres even for photos taken kilometres away from the glaciers.

This work has demonstrated the good potential of quantitative analyses carried out on old glacier photos. The results enable to integrate and constrain with high accuracy glacier reconstruction series based on observations of past length change, which are typically affected by gaps and inconsistencies. WWI photos are particularly useful because they cover a period with little or no observations in this geographic area.

The high potential of methods tested in this work is demonstrated also by new insights obtained on past 'marginal' glaciation and ELA variability. Glacierets such as those mapped using WWI photos on the Laghetti d'Albiolo cirque were never recognized before, because of insufficient geomorphological evidence and lack of information on previous glacier inventories. Considering their extent during the WWI and their possible larger extent during the LIA, it is possible that similar glacierets or small glaciers constituted a significant portion of the total LIA glacierized area. There are many sites with analogous characteristics in the Eastern Italian Alps. Our results suggest that a more comprehensive picture of these marginal glaciation areas can be obtained from quantitative analyses based on old photos.

Similar considerations can be done for the ELA variability in the past, which is conventionally analysed comparing zero-budget ELAs obtained from glacier geometries. This method is widely used, and provides information on persistent variations in the mean value of the ELA. However, they cannot account for the high inter-annual and inter-decadal variability of the ELA in the past. The snow lines and firn lines detected in the WWI photos document a significant lowering of the ELA in that period, in some cases below the LIA ELA reported in the literature. A considerable rise of the ELA in recent years is also evident from comparison with current satellite imagery, which is far above the variation obtained from glacier geometries alone.

This contribution can be considered as a starting point for systematic investigations on the glaciated landscape of the Eastern Italian Alps, based on old photos. The WWI photos are a unique information source on glacier variations, which is nevertheless still largely unexploited. The availability of photos – recently increased – in conjunction with new technologies such as the monoplotting, are significant developments with potential application even beyond the WWI period.

REFERENCES

Baroni C. & Carton C. (1990) - *Variazioni oloceniche della vedretta della Lobbia (Gruppo dell'Adamello, Alpi centrali).* Geografia Fisica e Dinamica Quaternaria, 13, 105-119.

Baroni C., Casale S., Salvatore M.C., Ivy-Ochs S., Christl M., Carturan L., Seppi R. & Carton A. (2017) - *Double response of glaciers in the Upper Peio Valley (Rhaetian Alps, Italy) to the Younger Dryas climatic deterioration.* Boreas, 46 (4), 783-798. doi: 10.1111/bor.12284

Bondesan A., Carton A. & Laterza V. (2015) - *Leo Handl and the Ice City (Marmolada Glacier, Italy).* Rendiconti Online della Società Geologica Italiana, 36 (2015), 31-34. doi: 10.3301/ROL.2015.137

Bozzini C., Conedera M. & Krebs P. (2012) - *A new monoplotting tool to extract georeferenced vector data and orthorectified raster data from oblique non-metric photographs.* International Journal of Heritage in the Digital era, 1 (3), 499-518.

Carturan L., Baldassi G.A., Bondesan A., Calligaro S., Carton A., Cazorzi F., Dalla Fontana G., Francese R., Guarnieri A., Milan N., Moro D. & Tarolli P. (2013) - *Current behaviour and dynamics of the lowermost Italian glacier (Montasio Occidentale, Julian Alps).* Geografiska Annaler: Series A, Physical Geography, 95, 79-96. doi: 10.1111/geoa.12002

Carturan L., Baroni C., Carton A., Cazorzi F., Dalla Fontana G., Delpero C., Salvatore M.C., Seppi R. & Zanoner T. (2014) - *Reconstructing fluctuations of La Mare Glacier (Eastern Italian Alps) in the Late Holocene: new evidences for a Little Ice Age maximum around 1600 AD.* Geografiska Annaler: Series A, Physical Geography, 96, 287-306. doi: 10.1111/geoa.12048

Čekada M. T., Zorn M. & Colucci R.R. (2014) - *Changes in the area of the Canin (Italy) and Triglav glaciers (Slovenia) since 1893 based on archive images and aerial laser scanning.* Geodetski Vestnik, 58 (2), 274-313.

Conedera M., Bozzini C., Scapozza C., Rè L., Ryter U. & Krebs P. (2013) - *Anwendungspotenzial des WSL-Monoplotting-Tools im Naturgefahrenmanagement. Schweizerische Zeitschrift für Forstwesen.* Schweizerische Zeitschrift fur Forstwesen, 164 (7), 173-180. doi: 10.3188/szf.2013.0173

Corripio J.G. (2004) - *Snow surface albedo estimation using terrestrial photography.* International Journal of Remote Sensing, 25 (24), 5705-5729.

De Marco J., Carturan L., Piermattei L., Cucchiaro S., Moro D., Dalla Fontana G. & Cazorzi F. (2020) - *Minor Imbalance of the Lowermost Italian Glacier from 2006 to 2019.* Water, 12 (9), 2503.

Desio A. (1923) - *Su di una forma particolare di ghiacciai delle Alpi venete.* Atti VIII Congresso Geografico Italiano. Firenze 29/3 - 6/4 - 1921; Vol II, comunicazioni (Ed. Artistiche Alinari, Firenze -1923).

Desio A. (1967) - *I ghiacciai del Gruppo Ortles-Cevedale.* Consiglio Nazionale delle Ricerche, Comitato Glaciologico Italiano, Milano, 875 pp.

Fluehler M., Niederoest J. & Akca D. (2005) - *Development of an educational software system for the digital monoplotting.* Proceedings of the ISPRS, Working group VI/1 - VI/2 (Tools and Techniques for E-Learning), Potsdam (Germany), June 1-3 2005, 6 pp.

Haeberli W. (1985) - *Creep of Mountain Permafrost: Internal structure and Flow of Alpine Rock Glaciers.* Mitteilung der VAW/ETH, 77, 119 pp.

Haeberli W., Oerlemans J. & Zemp M. (2019) - *The future of alpine glaciers and beyond.* Oxford Research Encyclopedia of Climate Science. Oxford University Press. doi: 10.1093/acrefore/9780190228620.013.769

Handl L. (1916) - *Von der Marmolata-Front.* Zeitschrift des Deutschen und Österreichischen Alpen-Vereines, 47, 212-218.

Handl L. (1917) - *Von der Marmolata-Front II.* Zeitschrift des Deutschen und Österreichischen Alpen-Vereines, 48, 149-161.

Hansche I. (2017) - *Assessment of the viability of worldwide application of the WSL Monoplotting Tool in reconstruction of past glacier stands. A set of trials using historical images of the Goldbergkees glacier (Austria) dating back to 1969.* Bachelor thesis, Dept. Geography and Regional Studies, Alpen Adria University, Klagenfurt, AT. 2017.

Kargel J.S., Leonard G.J., Bishop M.P., Kääb A. & Raup B.H. (Eds.) (2014) - *Global land ice measurements from space*, Springer, 876 pp.

Mackintosh A.N., Anderson B.M. & Pierrehumbert R.T. (2017) - *Reconstructing climate from glaciers.* Annual Review of Earth and Planetary Sciences, 45, 649-680.

Mattana U. (1995) - *Il ghiacciaio della Marmolada. Aspetti geomorfologici della fronte centrale.* Rivista Geografica Italiana, 102, 113-127.

Mitishita E.A., Machado A.L., Habib A.F. & Gonçalves G. (2004) - *3D monocular restitution applied to small format digital airphoto and laser scanner data.* Proceedings of Commission III, XXth ISPRS Congress (International Society for Photogrammetry and Remove Sensing), Istanbul (Turkey), July 12-23, 2004. Remote Sensing and Spatial Information Sciences, 35 (B3), 70-75.

Nussbaumer S.U. & Zumbühl H.J. (2012) - *The Little Ice Age history of the Glacier des Bossons (Mont Blanc area, France): a new high-resolution glacier length curve based on historical documents.* Climatic Change, 111 (2), 301-334.

Nussbaumer S.U., Zumbühl H.J. & Steiner D. (2007) - *Fluctuations of the Mer de Glace (Mont Blanc area, France) AD 1500-2050: an interdisciplinary approach using new historical data and neural network simulations.* Zeitschrift für Gletscherkunde und Glazialgeologie, 40, 1-183.

Pelfini M. (1994) - *Equilibrium line altitude (ELA) variations recorded by Ortles-Cevedale glaciers (Lombardy, Italy) from little ice age to present.* Geografia Fisica e Dinamica Quaternaria, 17, 197-206.

Porter S.C. (1975) - *Equilibrium line altitudes of late Quaternary glaciers in the Southern Alps, New Zealand.* Quaternary Research 5, 27-47.

Salvatore M.C., Zanoner T., Baroni C., Carton A., Banchieri F.A., Viani C., Giardino M. & Perotti L. (2015) - *The state of Italian glaciers: A snapshot of the 2006-2007 hydrological period.* Geografia Fisica e Dinamica Quaternaria, 38 (2), 175-198. doi:10.4461/GFDQ.2015.38.16

Scapozza C., Lambiel C., Bozzini C., Mari S. & Conedera M. (2014) - *Assessing the rock glacier kinematics on three different timescales: a case study from the southern Swiss Alps.* Earth Surface Processes and Landforms, 39 (15), 2056-2069.

Seppi R., Carton A., Zumiani M., Dall'amico M., Zampedri G. & Rigon R. (2012) - *Inventory, distribution and topographic features of rock glaciers in the southern region of the Eastern Italian Alps (Trentino).* Geografia Fisica e Dinamica Quaternaria, 35, 185-197.

Steiner L. (2011) - Reconstruction of Glacier States from Geo-Referenced, Historical Postcards. Master Thesis, ETH Zurich, Zurich, Switzerland, October 2011.

Wanner H., Beer J., Bütikofer J., Crowley T.J., Cubasch U., Flückiger J., Goosse H., Grosjean M., Joos F., Kaplan J.O., Küttel M., Müller S.A., Prentice I.C., Solomina O., Stocker T.F., Tarasov P. Wagner M. & Widmann M. (2008) - *Mid- to Late Holocene climate change: an overview.* Quaternary Science Reviews, 27 (19-20), 1791-1828.

WGMS (2015) - In Zemp M., and 7 others eds. Global glacier change bulletin no. 1 (2012-2013). ICSU(WDS)/IUGG(IACS)/UNEP/ UNESCO/ WMO, World Glacier Monitoring Service, Zurich, Switzerland, 230 pp., publication based on database version: doi:10.5904/wgms-fog-2015-11

Zemp M., Paul F., Hoelzle M. & Haeberli W. (2007) - *Glacier fluctuations in the European Alps 1850-2000: an overview and spatio-temporal analysis of available data.* In: Orlove B., Wiegandt E. & Luckman B. (Eds.) - The darkening peaks: Glacial retreat in scientific and social context. University of California Press, 152-167.

Zemp M., Frey H., Gärtner-Roer I., Nussbaumer S.U., Hoelzle M., Paul F., Haeberli W., Denzinger F., Ahlstrøm A.P., Anderson B., Bajracharya S., Baroni C., Braun L.N., Cáceres B.E., Casassa G., Cobos G., Dávila L.R., Delgado Granados H., Demuth M.N., Espizua L., Fischer A., Fujita K., Gadek B., Ghazanfar A., Ove Hagen J., Holmlund P., Karimi N., Li Z., Pelto M., Pitte P., Popovnin V. V., Portocarrero C.A., Prinz R., Sangewar C.V., Severskiy I., Sigurðsson O., Soruco A., Usubaliev R. & Vincent C. (2015) - *Historically unprecedented global glacier decline in the early 21st century.* Journal of Glaciology, 61 (228), 745-762.

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